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Origin of nonmonotonic T_c behavior in ferromagnet/superconductor structures

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Abstract

The original theory of proximity effect in the layered ferromagnetic metal/superconductor (FM/S) structures taking into account a finite transparency of FM/S interface as well as a competition between 1D and 3D Larkin–Ovchinnikov–Fulde–Ferrell (LOFF) states is developed. It is shown that the oscillatory dependence of critical temperature T_c on the FM layer thickness d_f is due to oscillations of the Cooper pairs flux at the FM/S boundary. This effect is possible not only in the FM/S multilayers, but in the FM/S bilayers as well. The phenomena of reentrant and periodically reentrant superconductivity in the FM/S bilayers and superlattices are predicted. The competition between 1D and 3D LOFF states leads to significant smoothing of the $T_c(d_f)$ dependence, so that in the most cases one maximum of this dependence is realized as this has been observed in Gd/Nb and Fe/Nb/Fe. © 2000 Elsevier Science B.V. All rights reserved.

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The experiments [1–6] testify the coexistence of superconductivity and ferromagnetism in the FM/S multilayers is exhibited in a qualitative different behavior of the dependence of the superconducting transition temperature T_c versus the FM layer thickness d_f for the same FM/S structures. In the experiments on Fe/V [1] and Gd/Nb [2] systems after the initial rapid drop with increasing d_f the T_c reaches a plateau; in other experiments with the same systems ([3] and [4,5], respectively), the T_c oscillates before reaching the plateau. The theoretical interpretation of $T_c(d_f)$ oscillations [6] reduces to periodic "switching" of the superconductivity type from the 0 phase to the π phase, with the sign of the order parameter Δ reversed as an FM layer is crossed. However, it has been found recently that $T_c(d_f)$ oscillations also occur in the Fe/Nb/Fe trilayers [7], where π-phase superconductivity is impossible in principle and cannot be described in the context of the theory [3].

We develop our theory [8–10] of proximity effect taking into account finite transparency of the FM/S boundaries and competition between diffusion-like and wave like of conduction electrons motion in the FM layers. In FM layers pairing conditions correspond to the LOFF mechanism with nonzero pairs momentum and with oscillating pair amplitude. The main equations for reduced temperature of superconducting transition $t = T_c/T_{cs}$ of FM/S structures are the same [8–10], but there is very essential variation. Wave number k_f describing a transversal spatial variations of pair amplitude into FM layers is determined now by expression $k_f^2 + q_f^2 = -2iI(1 + 2iI\tau_f)/D_f$ at $I \gg \pi T_{cs}$ and $2I\tau_f < 1$ ($D_f \Rightarrow 3D_f$ at $2I\tau_f > 1$). $\boldsymbol{q}_f$ is two-dimensional wave vector describing the plane oscillations. Here I is the FM layer exchange field, τ_f^{-1} is the collision rate of conduction electrons with nonmagnetic impurities, D_f is the FM layer diffusion coefficient. The value of the $\boldsymbol{q}_f$ should be found by an optimization of free energy value, i.e. from a maximum condition of T_c.

Some results of exact numerical analysis for FM/S structures are given in Fig. 1. Altering parameters in physically admissible range we can numerically obtain a wide diversity of variants of the $T_c(d_f)$ behavior: from the fast initial decrease with subsequent smooth output on a plateau, which was observed for the Gd/Nb bilayers

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